Developing a Predictive Capability for Bioluminescence Signatures

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LONG-TERM GOALS

Bioluminescence represents an operational threat to naval nighttime operations because the flow field associated with their motion stimulates naturally occurring plankton. In the littoral, the primary sources of bioluminescence are dinoflagellates, common unicellular plankton that are also known to form red tides. Dinoflagellate bioluminescence is stimulated by flow stress of sufficient magnitude to cause cell deformation, such as in the boundary layers of swimming animals, in separated flow of the wakes of animals, fixed objects, and ships, and in breaking surface waves, leading to spectacular displays of bioluminescence during periods of high dinoflagellate abundance. The oceans can be considered a luminescent minefield where bioluminescence is stimulated by flow disturbance. The bioluminescent signatures of some swimming fish are distinct enough to differentiate species; nocturnally foraging predators may use bioluminescent wakes to locate their prey.

The bioluminescence signature of a moving object depends on the bioluminescence potential of the organisms (related to their species abundance), the volume of the flow regions associated of sufficient shear stress, and its detectability from a surface observer based on radiative transfer of the light through the water and surface interface, as well as surface ambient light conditions. We are interested in predicting bioluminescence signatures, specifically in developing the capability to model flow stimulated bioluminescence and applying the model to a computational fluid dynamics model of the flow field of a moving object, and exploring mitigation strategies that reduce the bioluminescence signature to reduce the threat of detection of moving underwater vehicles.

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OBJECTIVES

An extremely challenging goal is the need to predict the intensity and spatial footprint of bioluminescence signatures of naval relevance. Advances in computational fluid dynamics (CFD) led by PI Hyman make it possible to model the flow around a moving object, and now a new bioluminescence stimulation (BIOSTIM) model developed by PI's Deane and Stokes (Deane and Stokes 2005) provides an initial capability to estimate bioluminescence levels as a function of flow properties, specifically fluid shear stress, which we have previously shown to be the flow property most closely correlated with flow-stimulated bioluminescence in primarily laminar flows (Latz et al. 1994; Latz et al. 2004; Latz and Rohr 1999; Maldonado and Latz 2007).

The overall scientific objectives of this project are to: (1) perform calibration experiments to determine the relationship between bioluminescence stimulation and fluid shear stress; (2) update the BIOSTIM model based on the calibration experiments results to include a high shear stress stimulation component; (3) evaluate computational approaches using Reynolds-averaged Navier-Stokes (RaNS) and Direct Numerical Simulation (DNS) solvers, to determine which is more suitable for bioluminescence predictions; (4) validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are characterized using CFD models, so that model predictions of bioluminescence intensity can be compared to experimental results; and (5) couple the BIOSTIM and CFD models to provide a unique flow visualization tool, which can be used to predict bioluminescence signatures for flow fields of naval interest.

APPROACH

The current probabilistic model for bioluminescence stimulation (BIOSTIM) contains three components to allow for: (1) direct stimulation by fluid shear stress, (2) rate-of-change of fluid shear stress, and (3) a memory term to allow for cell desensitization resulting from prolonged exposure to stimulation. The model is based on the fundamental assumption that over any small time interval there is a small but finite chance that a cell will flash, which depends on these three factors. This study considers the case of intense but brief stimulation lasting for no more than a few seconds. In this case we do not have to account for the effects of cell desensitization (von Dassow et al. 2005) and cell memory, greatly simplifying the experiments and analysis required to model the effects of turbulence.

The overall objective of this study is to obtain bioluminescence stimulation data under conditions of high shear stress to feed into the BIOSTIM model, which then is incorporated into CFD models to predict bioluminescence signatures created by bodies traveling in or on the ocean. The most generally applicable simulation techniques are algorithms that solve the Reynolds-averaged Navier-Stokes (RaNS) equations and compute the ensemble-averaged velocities, as well as turbulent energy and energy dissipation fields throughout a given flow, allowing an estimation of local (averaged) turbulent shear stress. The RaNS algorithm to be used in the proposed task is CFDSHIP-IOWA, a well-documented algorithm (Carrica et al. 2006) previously used by PI Hyman and verified with full-scale tests with many types of naval ships. However, such algorithms cannot resolve the very small scales that are responsible for bioluminescent stimulation. The action of such small-scale turbulence is approximately characterized by the averaged energy dissipation rate – a modeled quantity. In contrast, the BIOSTIM model, as currently written, is most appropriate for use in a Direct Numerical Simulation (DNS) solver. DNS solutions capture all relevant length and temporal scales in the flow including bioluminescence stimulatory scales (these are in the Kolmogorov or inertial range, depending on Reynolds number). To accomplish this, however, the solvers require extremely fine grids – grids that

become too large when flow simulation of model-scale vehicles is attempted and far too large to be considered for full-scale naval vehicles. Therefore the new bioluminescence stimulation model developed in Task 2 will accept the ensemble-averaged flow data produced during a practical flow simulation as a means of determining stimulation probability.

The final task is to validate the updated BIOSTIM model with laboratory tests involving independent flow fields that are modeled using computational fluid dynamics (CFD), so that model predictions of bioluminescence intensity can be compared to experimental results. It is critical to validate the updated BIOSTIM model to determine how predicted results compare to experimental measurements with independent flow fields. The BIOSTIM model is coupled to the CFD model of a body mounted in a flow field to predict levels of stimulated bioluminescence. A new vertical test tank with a 122 cm square cross section was used for the validation tests. Test bodies are attached to a non-stretchable line, which ran on an overhead pulley, and connected to a stepper motor under computer control for acceleration, speed, and distance. Speeds up to 4 m/s in air are possible with this setup. Bioluminescence was measured with a low-light digital camera system to quantify stimulation in the boundary layer and wake regions. The experimental results are then compared to the coupled BIOSTIM-CFD model predictions.

Figure 1. Vertical test tank used for ellipsoid bioluminescence tests. The test body (not shown) is attached to a string that is raised by a stepper motor under computer control. Speeds up to 1.5 m/s were achieved without appreciable unsteady motion. Bioluminescence was imaged by a low-light digital camera system under computer control.

WORK COMPLETED

The first goal for integrating the computational and experimental activities is to perform direct numerical simulations (DNS) of the flow field associated with a sphere for velocities of 0.5 and 1 m/s, to obtain 2D maps of local fluid shear stress. The current BIOSTIM model has been incorporated into the DNS results to predict levels of stimulated bioluminescence; these predictions are being compared to existing bioluminescence images of a sting-mounted sphere moving at the same speeds in a flume and imaged with a digital low-light camera.

1. Computational work. During the past year, work continued on improving the CFD simulation of flow, shear stress and related bioluminescent stimulation in the wake of a sphere. Computations in FY 10 were encouraging, but the stimulation probability computed from those solutions showed a much smaller geometry than the images from tow tank measurements. Therefore work in the current year focused on two avenues. The first was to improve the sphere solution and the second was to begin work on flow computations over an ellipsoid, to compare to experimental observations.

2. Experimental work. New observations of bioluminescence associated with a towed 6:1 ellipsoid 15 cm long were made in the vertical test chamber. Speeds up to 1.5 m/s were achieved without appreciable unsteady motion of the ellipsoid, with initial tests run for cultures of *L. polyedrum* at a concentration of 10 cells/ml. These observations are to be compared to computed predictions of bioluminescence for the ellipsoid.

RESULTS

1. Computational work. Close scrutiny of the earlier computations for a 32 mm diameter sphere moving at a speed of 1 m/s suggested that, while the grid resolution was approximately correct, adjustments would be very beneficial. Results using the original coarse grid configuration are shown for the center-plane instantaneous axial velocity field (Figure 2A) and the probability of bioluminescence stimulation (Figure 2B). The actual level of bioluminescence intensity depends on the stimulation probability and bioluminescence potential. Note that grid resolution on the upstream face of the sphere allows the solution to capture high shear stresses there, but low resolution downstream causes small-scale turbulent structures to be dissipated. The grid was altered in two steps; the first was to increase the high resolution region towards the downstream half of the body and to increase the lateral extent of that same region. This resulted in a 351 x 351 x 601 grid, for which the instantaneous velocity field is shown in Figure 2C and the stimulation field shown in Figure 2D. These results show a stimulated region extending roughly 2.0 diameters downstream of the body. In addition, this region is conical in geometry with the high shear (leading to high stimulation probability) concentrated on the body centerline. This is in contrast to that seen in the experimental observations, which show a stimulation field with a more cylindrical structure. It was the latter observation that motivated building yet another grid that had approximately the same resolution but extended that resolution much further downstream. Results from that (351 x 351 x 801) computation are shown in Figure 2E for the velocity field and Figure 2F for the corresponding stimulation field. While a grid convergence study has not been performed (clearly the grid was not converged in the earlier solutions), the fact that shear stress above the stimulation threshold does not extend to the end of the high resolution grid suggests that this grid is at or close to convergence. In addition, the stimulation field geometry is more similar to that seen in the tow tank images. The stimulation region extends nearly 2.5 diameters downstream and exhibits a roughly cylindrical shape. The solution strongly suggests that unsteady vortex shedding should lead to a stimulation field a little larger than the sphere diameter, a prediction not seen in the

tow tank images. In addition, the maximum stimulation probability is a small distance downstream of the body, also in contrast to the images.

The second focus was to provide high resolution computations of the flow over a 15 cm long 6:1 ellipsoid. These were initiated late in the year and the results to date have not been useful. In an effort to reduce computational cost, symmetry was utilized and that appears to have dampened the formation of turbulent flow. Because of the very high resolution used in this grid, the maximum time-step was 2×10^{-6} seconds (i.e., 2 μs) (for comparison, the sphere grid required a time-step of 5×10^{-5} s or 50 μs) and a very long time (calendar and computational) was required to reach a stationary solution and realize the error. Over the coming months, the grid will be altered to remove symmetry and to slightly reduce resolution.

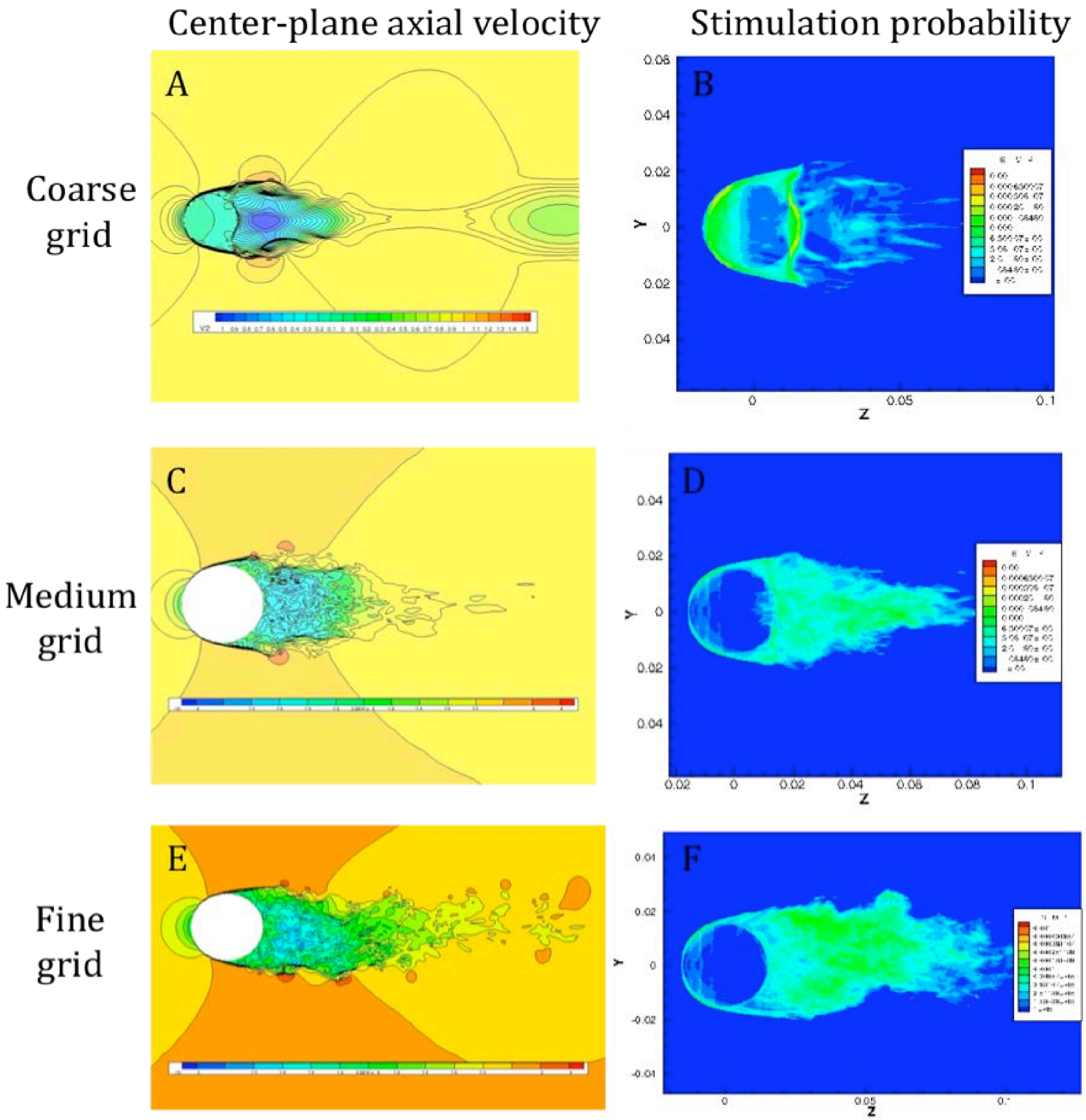

Figure 2. Contour plots for a 32 mm diameter sphere, moving to the left at a speed of 1 m/s, of computed center-plane instantaneous axial velocity field (left column) based on direct numerical solutions, and the probability of bioluminescence stimulation (right column) around a sphere, based on integrating the computational flow dynamics model with the bioluminescence stimulation model. (A-B) Results for the original coarse resolution grid. (C-D) Results for a medium resolution 351 x 351 x 601 grid. (C-D) Results for a fine resolution 351 x 351 x 801 grid. The stimulation region extends nearly 2.5 diameters downstream and exhibits a roughly cylindrical shape. The solution strongly suggests that unsteady vortex shedding should lead to a stimulation field a little larger than the sphere diameter, and that maximum stimulation probability is a small distance downstream of the body.

2. Experimental work. Bioluminescence associated with the motion of a 15 cm long 6:1 ellipsoid at speeds up to 1.5 m/s were run in the vertical test tank containing *L. polyedrum*. Low-light digital images showed bioluminescence associated with the boundary layer and immediately downstream (Figure 3). These observations will be compared to computed predictions for bioluminescence.

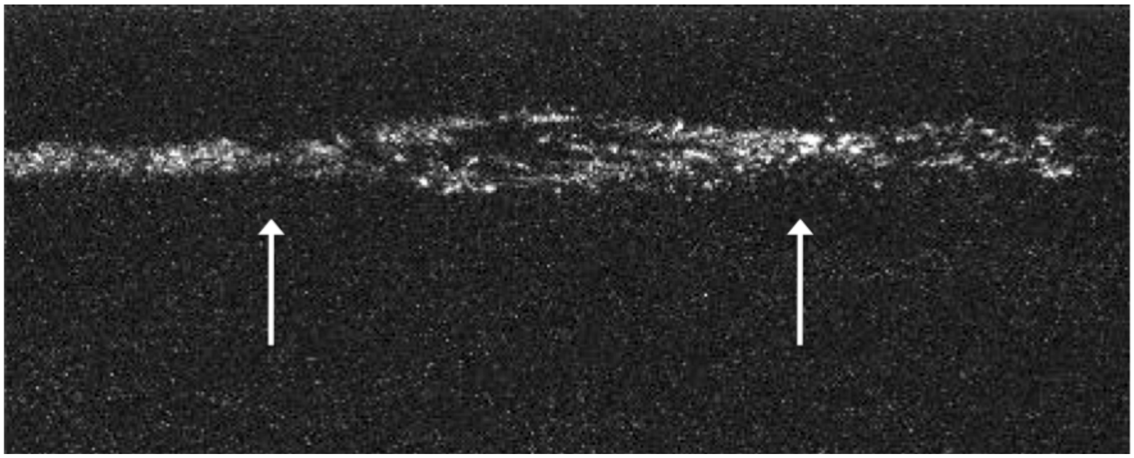

***Figure 3. Bioluminescence of* Lingulodinium polyedrum *at a concentration of 10 cells/ml associated with a 15 cm long 6:1 ellipsoid moving to the left at a speed of 1.5 m/s. Bioluminescence was imaged by a low-light digital camera system. Bioluminescence is associated with the ellipsoid boundary layer (between arrows) and immediately downstream (to the right of the right arrow). Light upstream of the ellipsoid (left of left arrow) is from the string that is pulling the ellipsoid*.**

IMPACT/APPLICATIONS

Project results will enhance DoD capability for predicting levels of bioluminescence associated with surface and underwater vehicles of naval interest. The BIOSTIM model can be used in applications involving swimmer delivery vehicles and other submersible platforms, as well as torpedoes and other high-speed objects. The breakthrough in providing this capability is the development and application of the BIOSTIM model, developed by Deane and Stokes, that forms a theoretical basis for studying the relationship between flow stimulation and the bioluminescence response. The BIOSTIM model, when coupled to computational hydrodynamics models that provides values of shear stress for a given flow field, allows for predictions bioluminescence intensity for a given level of bioluminescence potential, either measured directly or obtained from the NAVOCEANO METOC database once a transfer function between the flow agitator and flow field is known.

A coupled BIOSTIM-CFD model introduces a new predictive capability for estimated bioluminescence signatures. A validated model can then be verified with full-scale experiments with surface ships and underwater vehicles of naval interest. In situations where field tests are not possible, once a transfer function between the flow agitator and flow field is known, it can be used with the NAVOCEANO METOC database of bioluminescence potential measurements to predict bioluminescence signatures in essentially any oceanic region. The Non-acoustical Optical Vulnerability Assessment Software (NOVAS) being developed by NRL (Matulewski and McBride 2005) has a placeholder in which the coupled BIOSTIM-CFD model can be incorporated into the nighttime visibility assessment component.

RELATED PROJECTS

The objectives of this project are complimentary and related to the objectives of an NSF funded project to better understand energy dissipation within breaking wave crests using the bioluminescent flash response of dinoflagellates as a flow visualization tool.

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